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14. ABSTRACT Wideband sonar transducers find many applications in underwater vehicles. Two methods can be used to design wideband acoustic transducers. The multiply resonant transducer concept has found very limited operational application. Also, new piezoelectric materials have been developed that have very high electromechanical coupling coefficient and provide wider bandwidth. However, no study to date has compared these two design methods for performance and cost differences, and none has investigated the possible additional benefits of combining the two methods in a single transducer element for greater benefit than is available from either separately. That is the objective of the present study.					
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Contract Information

Contract Number: N000141010492

Contract Title: Wideband Sonar Arrays for UUV and Weapon System Applications

Program Officer: Maria Medeiros

CO-PI Information:

- None

Abstract

Wideband sonar transducers find many applications in underwater vehicles. Two methods can be used to design wideband acoustic transducers. The multiply resonant transducer concept has found very limited operational application. Also, new piezoelectric materials have been developed that have very high electromechanical coupling coefficient and provide wider bandwidth. However, no study to date has compared these two design methods for performance and cost differences, and none has investigated the possible additional benefits of combining the two methods in a single transducer element for greater benefit than is available from either separately. That is the objective of the present study.

Technical Section

Technical Report File: [N0001410104921.doc](#) Cleared for Public Release

Slide File: [N0001410104921.ppt](#)

Progress Statement

Activity at the beginning of the Fiscal Year was delayed by the late delivery of the single crystal piezoelectric parts for the transducers. Delivery of the piezoelectric rings was promised in August 2011, but did not actually occur until late November. In the early months of 2012, Mr. Wilson built a single transducer element of his design to verify the assembly processes and procedures. Electrical bench tests of this element showed good performance throughout the frequency region of the two resonances and indicated that the modeled predictions should be obtained in water. When a second element was built, its alumina (ceramic) headmass broke when the element was prestressed. Further element build was put on hold until the reason for this failure was identified. A more careful finite element analysis of the element under prestress identified that the static stress in the head near the stress bolt was high enough to cause concern in high power testing. It is likely that this relatively high stress in combination with a minor defect in the head caused the failure, as the first assembled transducer does not exhibit this failure. Further assembly of the remaining elements, leading to acoustical testing in the ARL Acoustic Test Facility would have followed. At that time, however, Mr. Wilson encountered health problems that interfered with his ability to complete the work as scheduled. Project funds were exhausted in June 2012, and while Mr. Wilson did some work through the summer he has not been able to complete his degree. The Graduate Program in Acoustics and his thesis advisors would be happy to assist Mr. Wilson if he is able to return and complete his degree.

Refereed Journal Articles

- None

Books And Chapters

- None

Technical Reports

- None

Contributed Presentations

- Description: Description: Michael B. Wilson, Steophen C. Thompson and Thomas B. Gabrielson, "Design comparison of wideband tonpilz transducers using multiply resonant structures adn high coupling materials," presented at the International Workshop on Acoustic Transduction Materials and Devices, Penn State University, May 8-10 2012.
Date: May, 2012

Patents

- None

Honors

- None

Related Sponsored Work

- None

ONR Statistics

Grad Students(total):	1
PI/Co-PI Women:	0
PI/Co-PI Minority:	0
Grad Students Women:	0
Grad Students Minority:	0
Post Docs Students:	0
Post Doc Women:	0
Post Doc Minority:	0
Under Grad Students(total:	0
Under Grad Students Women:	0
Under Grad Students Minority:	0
Degrees Granted:	0
Invention disclosures citing ONR support:	0
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Contract Information

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Title of Research	Wideband Sonar Arrays for UUV and Weapon System Applications
Principal Investigator	Thomas B. Gabrielson
Organization	Applied Research Laboratory, Penn State University

Technical Section

Technical Objectives

The overall technical objective of the proposed project is to develop the analytical and experimental understanding of wideband underwater transducer design options, to provide the transducer designer with the tools and understanding to know what combination of new materials and transducer structures will provide the best solution for a given set of requirements.

At the completion of this project, information and computer models will be available to provide answers to the following questions for a given set of transducer system bandwidth and power requirements:

1. Can the requirements be met with a conventional tonpilz design and conventional PZT materials, and what are the requirements on the transmit amplifiers using the conventional design and materials?
2. Compared to the solution in 1, what improvements can be made in the performance and what simplifications result in the electronics with a multiply resonant transducer design using PZT materials? What is the relative cost of these performance improvements?
3. Compared to the solution in 1, what improvements can be made in the performance and what simplifications result in the electronics with the use of high coupling coefficient materials? What is the relative cost if these performance improvements?
4. Compared to the solutions in 2 and 3, what improvements can be made in the performance and what simplifications result in the electronics with the combined use of multiply resonant transducer structure and high coupling coefficient materials? What is the relative cost of these performance improvements?

Technical Challenges

There are difficulties in drawing unambiguous conclusions on the relative merits of a particular transducer design apart from a specific set of performance requirements. A simple design using relatively inexpensive materials that minimally achieves a set of requirements is probably the least expensive acceptable solution for that case. The added cost for new materials and the added assembly complexity of a multiply resonant transducer structure are only justified if they are necessary to meet the application requirements. This program must start with several sets of requirements that span the range from conventional to significantly aggressive improvements over current operational systems.

A further challenge is that the transducer design has a significant impact on the design of the transmit amplifier and the interface electronics. Some methods of obtaining a wideband flat transmitting response in a transducer element also provide a highly reactive electrical input impedance in a part of the flat response band. The transmit amplifier is then required to drive a highly reactive load which has a negative impact on the cost and power efficiency of the system. A better approach is to consider the design of the

transducer array, the interface electronics and the transmit power amplifiers to be parts of a single design challenge. It may be cost effective to use a more capable transducer if it reduces the cost and complexity of the transmitting amplifier.

Technical Approach

The proposed work is a coordinated program of analysis, fabrication and test of the transducer element, array and driving electronics to be performed by Mr. Michael B. Wilson, a student in the Graduate Program in Acoustics at Penn State University. The effort will start with a literature review of other previous wideband transducer and array projects using either high coupling coefficient materials or multiply resonant transducer structures. It will include a trip by the student and the PI and to NUWC, Newport RI, to visit with people from the Sensors and Sonar Systems Department to discuss their past activities and modeling methods that are relevant to the work of this project. Phase I will conclude with the definition of the common methods to be used for comparing the performance of transducers built with different materials and structures.

In the first school year, Mr. Wilson has become familiar with the methods of transducer design and with the analysis methods needed for the project. Progress for the school year includes the development of transducer models specifically for analyzing the performance of transducer elements and arrays of multiply resonant transducers, and of elements and arrays using high coupling coefficient materials.

During the second year, a detailed analysis has been performed of the comparative performance of transducers and arrays to answer the four questions posed in the Technical Objectives section. In addition, the student has designed and is purchasing parts to build and test a single element and project the performance that would be available from an array of multiply resonant transducers constructed using high coupling coefficient active transduction materials. This combination of transduction material and structure has not been built before, and it is anticipated that there may be design challenges and performance advantages not evident from previous work.

Mr. Wilson is working toward an M.S degree in Acoustics. His thesis is expected to be completed in the second year of the contract. The work will be documented by one or more technical papers for publication in archival journals such as *The Journal of the Acoustical Society of America*.

Progress Statement Summary

In the first fiscal year of the contract (FY10, partial year funding), the student has gained a general understanding of the design and performance of sonar transducers and methods of transducer modeling. He has examined the literature of previous to obtain wide bandwidth transducer operation using either multiply resonant transducer structures or high coupling materials, and he has initiated an analytical investigation of specific designs that might be appropriate for later prototype investigation. The conceptual design requirements for this study are a tonpilz transducer element intended for operation in a large array, in which the array has a low frequency band limit of 10 kHz and a high frequency limit as possible subject to the constraints that the transmitting response be flat within 10 dB and the transmitting power factor be greater than 50%. During FY11, the specific design requirements for the transducer to be built as a prototype have been determined, component parts sketches suitable to acquire the prototype parts have been made, and the parts are being purchased to build the transducer elements. With the funding that remained in FY12, it was planned that the prototype elements would be built and tested to verify the predictions made for operation in a full array. Unfortunately, the student encountered a health problems that interfered with his progress. Mr. Wilson was able to build and bench test a single transducer element. The electrical testing results from this element compared well with the model. Funding from this grant was exhausted in approximately June 2012. Support for Mr. Wilson was extended through August using internal funds from the Applied Research Laboratory, but he was not able to complete his degree.

Note that the conceptual requirements in use in this project are not intended for any specific system, but with simple modification and scaling might be appropriate for many. For the prototype element, the operating band was moved to a higher frequency to allow for more economical purchase of the single crystal piezoelectric parts. The operating band of the prototype units is expected to be at least two octaves, from 20 kHz to 80 kHz.

Progress

For FY10

Singly resonant tonpilz transducers built with PZT piezoelectric material are the long term standard for use in sonar arrays. Devices of this type can often achieve transmitting bandwidths of one-third to one-half octave if with a power factor greater than 0.5. In the mid-1980s, the doubly resonant transducer structure was developed and patented by the PI of this contract when he was working in industry. That structure has generally been able to provide an octave or slightly more bandwidth with high power factor. An example of this type is shown in Figure 1, from the work of Stephen Butler at NUWC¹.

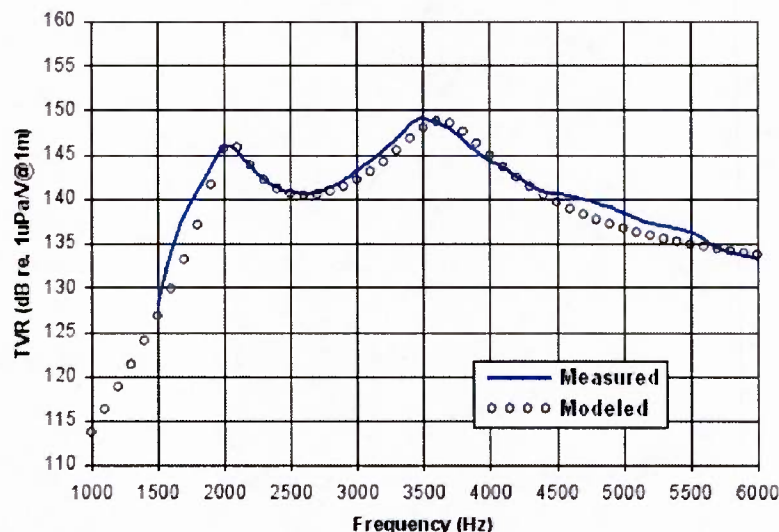
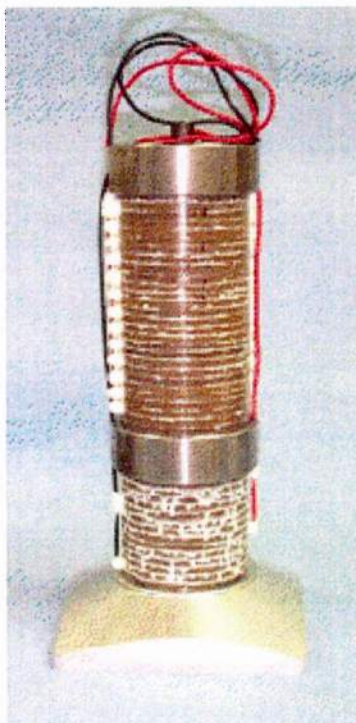


Figure 1 – A doubly resonant transducer element built with PZT ceramic that achieves a bandwidth of approximately one octave. (Figures from reference 1.)

Figure 2 shows a transducer and its transmitting voltage response for a singly resonant transducer element made with a high coupling piezoelectric material². This device has a high transmitting power factor in the band from 15 kHz to 30 kHz, and a flat transmitting band for a half octave higher in frequency. The devices of Figures 1 and 2 are the prior art against which the work of this contract should be compared.

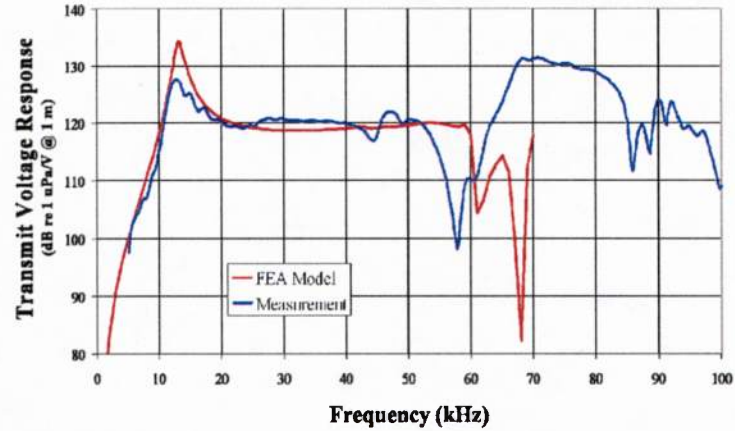


Figure 2 – A singly resonant tonpilz transducer built with PMN-PT single crystal piezoelectric material achieves an octave of bandwidth with high transmitting power factor and an additional half octave of flat transmitting bandwidth having poorer power factor.

As an exercise in reproducing the capabilities of the prior art, a conceptual design of each of the prior art structures has been performed. Figure 3 shows the transmitting and receiving responses for a doubly resonant element built with PZT material. The transmit operating band is defined as the region over which the transmitting power factor is greater than 0.5, or the electrical input impedance phase is less than 60° .

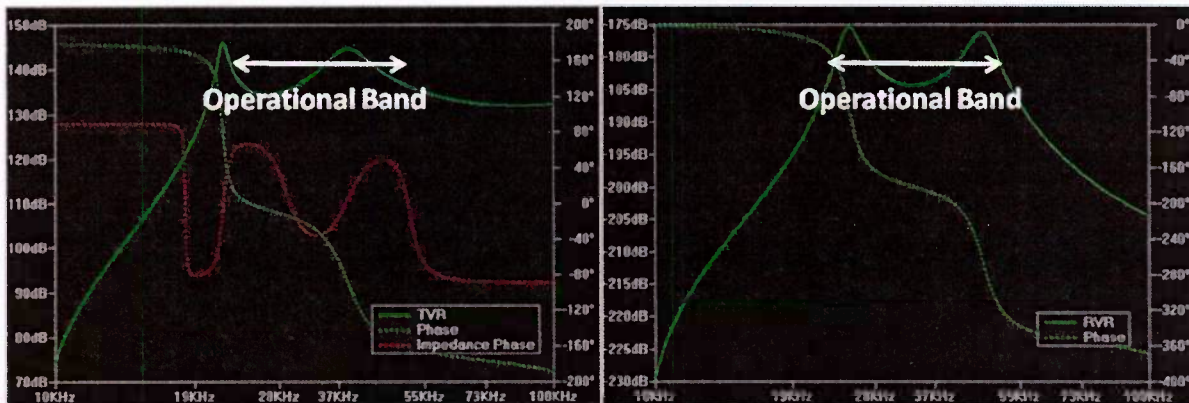


Figure 3 – Transmitting Voltage Response (left) and Receiving Voltage Response (right) for a doubly resonant transducer element built with PZT.

Figure 4 shows the same responses for an element using single crystal piezoelectric material. Again, the transmitting band is defined as the frequency region in which the transmitting power factor is greater than 0.5. For both of the transducers in Figures 3 and 4, the operating bandwidth is approximately one octave.

The follow-on from this will be to extend the design to doubly resonant transducers in which one and then both of the piezoelectric stacks are implemented with high coupling piezoelectric material.

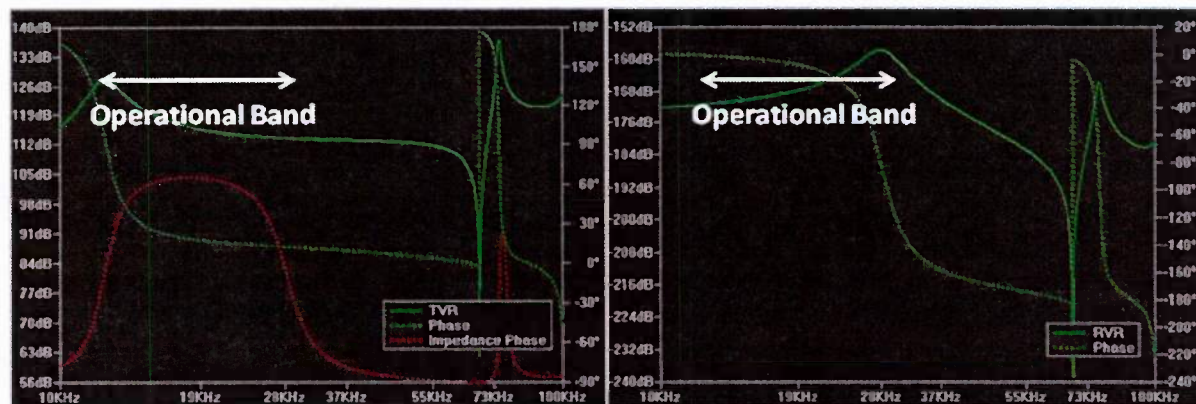


Figure 4 - Transmitting Voltage Response (left) and Receiving Voltage Response (right) for a singly resonant transducer element built with single crystal PMN-PT piezoelectric material.

For FY11

In a general study such as this, there are really too many design variables to consider every possibility. The range of materials and designs, both conventional and new, is far too extensive. Thus, the more detailed analytical studies in this year are based on a number of simplifying assumptions.

- The study will use two widely available materials: The conventional material designs will all use a PZT-4 material with a material electromechanical coupling coefficient of 0.70. The high coupling material in all cases will be PMN-0.28PT, with a material electromechanical coupling coefficient of 0.90. These materials are readily available from multiple sources. Material property data for is taken from Sherman and Butler³.
- Matching layers at the transducer face are not included in the analysis. A suitable matching layer may extend the bandwidth of any of the example designs by approximately the same amount.
- Electrical tuning elements are not included in the design. For singly resonant transducers, electrical tuning is known to provide some advantages in matching the transducer to its amplifier. However these advantages extend over a bandwidth much smaller than that envisioned in the wideband arrays.
- The multiply resonant transducers in this study will be driven by a single amplifier per element. With two piezoelectric stacks in the multiply resonant elements, it would be possible to drive the stacks from separate power amplifiers. The disadvantage of single amplifier drive is that the capacitance of each stack adds electrical loading to the input of the other stack. Separating the electrical drive can provide a performance advantage to outweigh the added cost and complexity of the additional amplifier and wiring in particular applications. This complexity is not included in the study.

Figure 5 shows the Transmitting Voltage Response (TVR) for singly resonant and doubly resonant transducers, both made with PZT-4 piezoelectric material. Figure 6 shows the transmit power factor for the two designs. The conventional transducer can achieve approximately one half octave of bandwidth with power factor greater than 0.5, while the doubly resonant element provides a full octave.

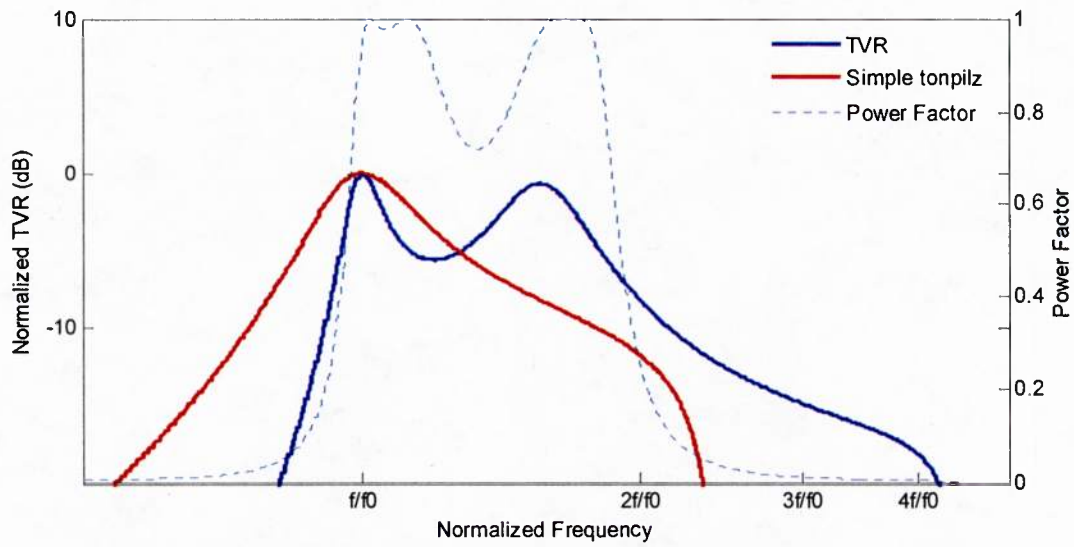


Figure 5 – Transmitting Voltage Response for singly and doubly resonant transducers built with PZT-4 piezoelectric material. Also shown is the transmit power factor for the doubly resonant unit.

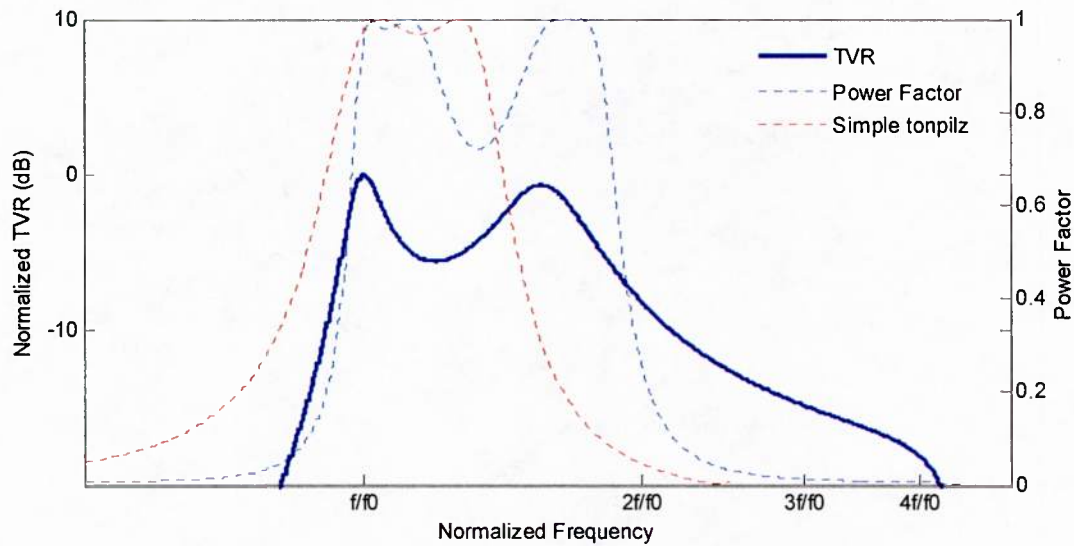


Figure 6 – Comparison of the power factor available from the singly and doubly resonant elements made with PZT-4.

Figure 7 shows a comparison of two singly resonant elements, one made with PZT-4 and the other with high coupling single crystal piezoelectric material. The high coupling element can achieve well over an octave of high coupling bandwidth. Note that the bandwidth between $3f_0$ and $4f_0$, which might often be counted in the transmit operating band, has quite a low power factor, and would be difficult to drive with many power amplifier designs. It is not included in the transmitting bandwidth with the definition used here.

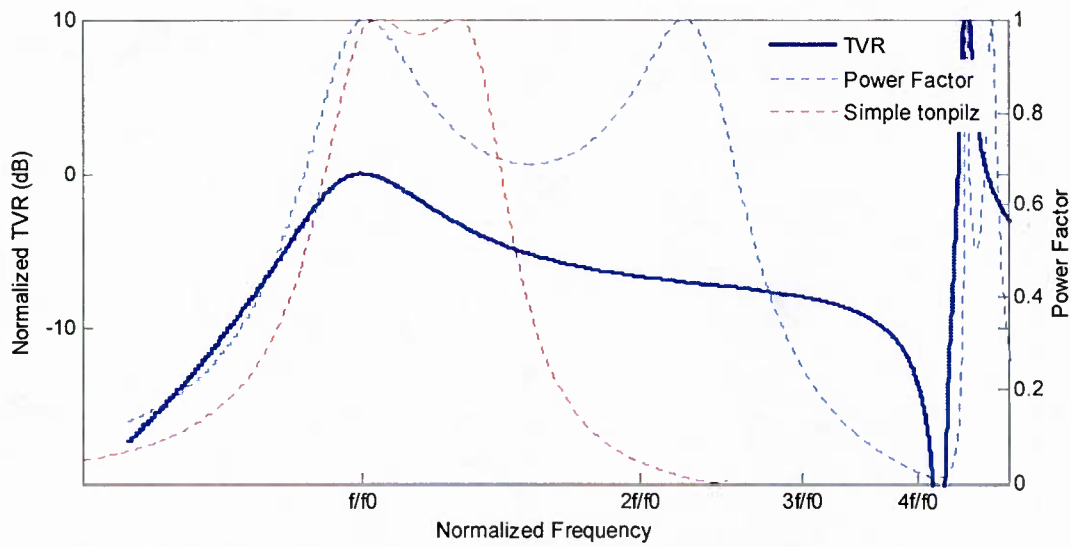


Figure 7 – TVR and power factor for a singly resonant element made high coupling piezoelectric material.

When considering the doubly resonant element with high coupling material, three different configurations are possible. The high coupling material can be placed in only the front stack, only the rear stack or in both stacks. All of these configurations were analyzed. There is an additional challenge in the designs that have one stack of PZT-4 and the other of high coupling material, in that the compliance of the high coupling material is very much higher than that of the PZT. With reasonable part sizes, this makes it difficult to balance the compliances of the two stacks in the manner necessary to achieve proper operation. Neither of these two configurations was found to have any advantage over the much simpler singly resonant high coupling element of Figure 7.

The doubly resonant element with high coupling material in both stacks does have significantly better bandwidth, as is shown in Figure 8. This design has over two octaves of bandwidth with transmit power factor greater than 0.5. Note in Figure 8 that the TVR level of the two TVR peaks is not the same. This was a compromise in the design to allow the two piezoelectric stacks to be built using the single crystal pieces of the same dimensions. The cost of single crystal purchase was significantly reduced by this decision, and it is relatively simple to adjust the drive level as a function of frequency to compensate for the known variation of TVR and achieve a flat spectral response in the medium.

Figure 9 shows a sketch of the transducer element that will be built. It has two piezoelectric rings in the front stack and four in the rear stack. The head is aluminum, carefully designed to have its flexural resonance frequency well above the upper band limit. The center mass and tail mass are fabricated from tungsten to achieve the proper mass in a compact part and eliminate undesired longitudinal resonances in the operating band.

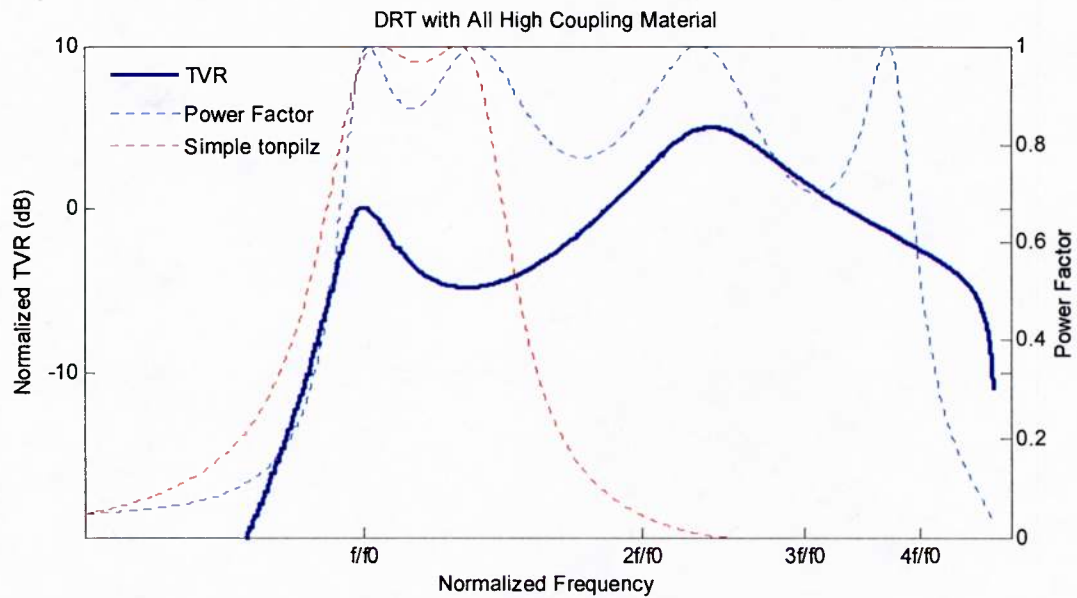


Figure 8 – The doubly resonant element using high coupling material in both stacks has a bandwidth with high power factor of over two octaves.

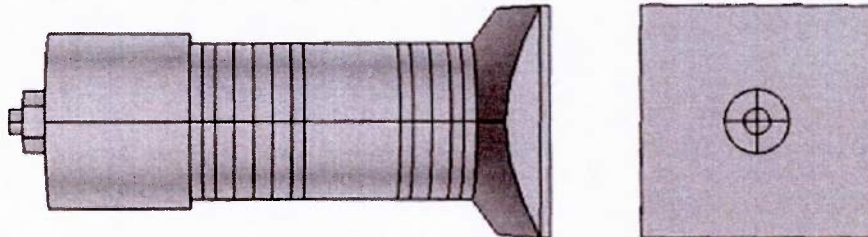


Figure 9 – Sketch of the prototype transducer element under construction.

The final unnormalized TVR and power factor for the prototype design under construction are shown in Figure 10. The single crystal parts have been purchased, and the fabrication of other parts is underway at the time this report is written.

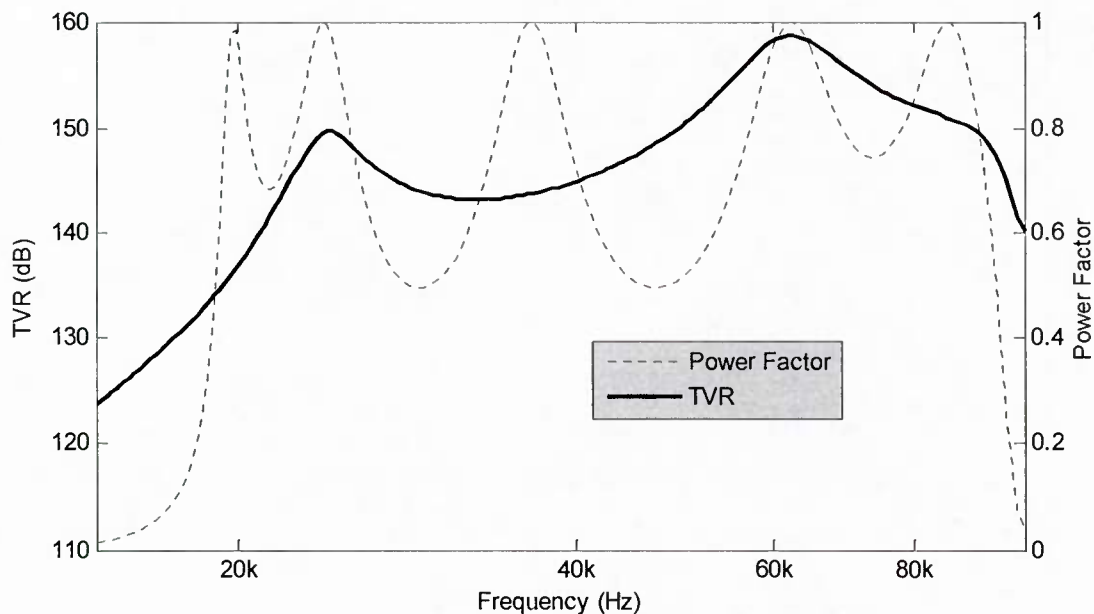


Figure 10 – The TVR and power factor expected for the prototype design.

For FY12

Activity at the beginning of the Fiscal Year was delayed by the late delivery of the single crystal piezoelectric parts for the transducers. Delivery of the piezoelectric rings was promised in August 2011, but did not actually occur until late November. In the early months of 2012, Mr. Wilson built a single transducer element of his design to verify the assembly processes and procedures. That element is shown in Figure 12. Electrical bench tests of this element showed good performance throughout the frequency region of the two resonances and indicated that the modeled predictions should be obtained in water.

When a second element was built, its alumina (ceramic) headmass broke when the element was prestressed. Further element build was put on hold until the reason for this failure was identified. A more careful finite element analysis of the element under prestress identified that the static stress in the head near the stress bolt was high enough to cause concern in high power testing. It is likely that this relatively high stress in combination with a minor defect in the head caused the failure, as the first assembled transducer does not exhibit this failure.

Further assembly of the remaining elements, leading to acoustical testing in the ARL Acoustic Test Facility would have followed. At that time, however, Mr. Wilson encountered health problems that interfered with his ability to complete the work as scheduled. Project funds were exhausted in June 2012, and while Mr. Wilson did some work through the summer he has not been able to complete his degree. The Graduate Program in Acoustics and his thesis advisors would be happy to assist Mr. Wilson if he is able to return and complete his degree.

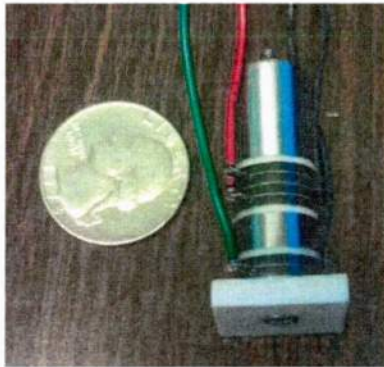


Figure 11 – The first transducer element verified the assembly processes and procedures as verified by electrical bench testing.

REFERENCES

- ¹ Stephen C. Butler, "Development of a High-Power, Broadband, Doubly Resonant Transducer (DRT)," Naval Undersea Warfare Center, Division Newport, 26 November 2001.
- ² Stephen C. Thompson, Richard J. Meyer and Douglas C. Markley, "Coupling Coefficient of Segmented Stack Transducers using High Coupling materials," presented at the U.S. Navy Workshop on Transduction materials and Devices, May 2008.
- ³ Charles H. Sherman and John L. Butler, *Transducers and Arrays for Underwater Sound*, Springer, 2007.

Wideband Sonar Arrays for UUV and Weapon System Applications



Project Start Date: 2010 February
Project End Date: 2012 June

Objectives:

Wide sonar bandwidth + advanced processing enables improved system capabilities. However transmit/receive bandwidth greater than one octave remains an emerging technology

- Multiply resonant devices are an option
- High coupling materials are now a viable option
- No study to date of a multiply resonant device that uses a high coupling material

Objective: Develop analytical and practical understanding, and a set of design guidelines for the design of elements for wideband sonar arrays having bandwidth greater than one octave

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ONR Sponsors:

Maria Medeiros, Ray Soukup

Product Schedule/ Milestones

- Model current technology - doubly resonant element, high coupling element
- Model doubly resonant element using high coupling material
- Build prototype
- Test prototype and analyze performance

Current Status/ Accomplishments

- Modeling completed for current technology, doubly resonant element using high coupling material
- Construction completed of a prototype doubly resonant element using high coupling material